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EPA FABRIC FILTRATION STUDIES: 4. BAG AGING EFFECTS

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16 ABSTRACT: The report gives results of a study to determine the effects of aging on filter bags made of woven polyester. Fabric filter life can be divided into three periods: break-in, steady-state, and wear-out. During the break-in, both bag collection efficiency and the pressure drop across the bag increase. In the steady-state, performance parameters remain relatively constant until the fabric begins to fail catastrophically (bag efficiency and pressure drop both decrease), signalling the onset of the wear-out. The transition between the break-in and the steady-state can be interpreted in terms of dust buildup in or on the fabric, ending in a steady-state in which the dust arriving during a complete filtration cycle equals that leaving during the same period. Dust permanently added to the fabric filter during the break-in is at "bulk" sites--sites which are not emptied during the shake-cleaning step of the cycle. Dust can be emitted or lost from these sites, however, as is evident from baghouse operation with clean air only and from performance measurements made after washing the fabric filter with soap and water. The report presents evidence that supports a further subdivision of the dust trapped at bulk sites into: that which is loosely bound and which affects bag pressure drop primarily; and that which is more tightly held and which influences bag collection efficiency primarily.

17 KEY WORDS AND DOCUMENT ANALYSIS

a DESCRIPTORS	b IDENTIFIERS/OPEN ENDED TERMS	c COSATI Field/Group
Air Pollution	Air Pollution Control	13B 21B
Fly Ash	Stationary Sources	11G
Dust	Particulate	11D
Filtration	Fabric Filters	13K
Dust Filters	Baghouses	11E
Woven Fabrics		
Polyester Fibers		

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EPA FABRIC FILTRATION STUDIES: 4. BAG AGING EFFECTS

by

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(*)

ABSTRACT

Fabric filter life can be divided into three periods: (1) break-in; 2) steady-state; and 3) wear-out. During the break-in period, bag collection efficiency increases, but pressure drop across the bag also increases. In the steady-state period, performance parameters remain relatively constant until the fabric begins to fail catastrophically (bag efficiency and pressure drop both decrease), signaling the onset of the wear-out period.

The transition between the break-in and steady-state periods can be interpreted in terms of dust buildup in or on the fabric, ending in a steady state in which the dust arriving during a complete filtration cycle equals that leaving during the same period. Dust permanently added to the fabric filter during the break-in period is located at "bulk" sites--sites which are not emptied during the shake-cleaning step of the cycle. Dust can be emitted or lost from these sites, however, as is evident from baghouse operation with clean air only and from performance measurements made after washing the fabric filter in soap and water. The evidence presented here supports a further subdivision of the dust trapped at bulk sites into: 1) that which is loosely bound and which affects bag pressure drop primarily; and 2) that which is more tightly held and which influences bag collection efficiency primarily. This preliminary classification of dust trapped at bulk sites requires more study, being based at present on only one observation of the dramatic effect of hand-washing a dust-loaded bag in soap and water. Alternative hypotheses could be equally plausible.

The total quantity of dust trapped at bulk sites varies with bag operating conditions. The dependence of bag life upon the quantity of trapped dust in the fabric is not known.

PREFACE

This report is the fourth in a series of reports, entitled EPA Fabric Filtration Studies, which summarize the results of EPA laboratory testing of new baghouse fabric materials and present the conclusions of specialized research studies in fabric filtration. These tests have been carried out over the past 4 years by the Industrial Environmental Research Laboratory, Research Triangle Park, N. C. and previously by predecessor agencies. The purpose of these investigations was to evaluate the potential of various new fabrics as baghouse filters and to obtain data for use by the fabric filtration community. The testing consisted of simulating a baghouse operation in a carefully controlled laboratory setting that allowed measurement and comparison of bag performance and endurance. The simulation discussed in this paper covered only a very narrow range of operating conditions:

1) Redispersed, classified flyash (mass median diameter about 4.0 μm) entrained in air was the only dust used.
2) All filtering was done at room temperature.
3) Relative humidity was either held at 50 percent or randomly varied from about 30 to 70 percent.
4) The air to cloth ratio was fixed at 4:1.
5) The inlet dust loading was held in the vicinity of 3 grains/ft^3 (6.9 g/m^3)*.

*EPA policy is to use metric units only or to list both the common British unit and its metric equivalent. For convenience and consistency with existing baghouse conventions, British units are used in this report. Readers more familiar with the metric system may use the factors in the Appendix to convert to that system.

Extreme caution should be used in extrapolating the results reported here to the substantially different conditions that occur in all field applications. The usefulness of the present results is primarily as either an initial screen of candidate fabrics for baghouse applications or as an exploration of baghouse phenomena.

The projected EPA Fabric Filtration Studies series consists of the following reports:

1) Performance of Non-Woven Nylon Filter Bags [Ref. 1].
2) Performance of Non-Woven Polyester Filter Bags [Ref. 2].
3) Performance of Filter Bags Made from Expended PTFE Laminate [Ref. 3].
4) Bag Aging Effects (this report).
5) Bag Cleaning Technology.
6) Analysis of Collection Efficiency by Particle Size.

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LIST OF ABBREVIATIONS AND SYMBOLS

A = filtration area of fabric (sq ft)

C_o = mass outlet concentration (grains/1000 cu ft)

E = mass collection efficiency (percent)

K_2 = true value of specific cake resistance (in. H_2O/fpm)/(lb/sq ft)

K_2' = measured value of specific cake resistance (in. H_2O/fpm)/(lb/sq ft)

ΔP_E = pressure drop across bag extrapolated to time zero of filtration cycle (in. H_2O)

ΔP_T = pressure drop across bag at end of filtration cycle (in. H_2O)

S_E = effective drag (in. H_2O/fpm)

S_T = terminal drag (in. H_2O/fpm)

A/C = air/cloth ratio (fpm)

SECTION I

INTRODUCTION

The life of a fabric filter can be divided into three stages:

1) A break-in period in which its measures of performance are continually changing. Typically collection efficiency and pressure drop increase from cycle to cycle; specific cake resistance does not generally change much but the number of penetrating particles continually decreases between successive cycles. Residual dust cake in and on the fabric continually builds up.
2) A lengthy steady-state period characterized by stable bag performance. Initial pressure drop following each cleaning cycle remains essentially constant; bag collection efficiency is uniformly high, and outlet concentrations are low. Performance parameters cycle between stable end points before and after cleaning.
3) The wear-out period in which tears and holes appear in fabric because of physical or chemical wear. Bag efficiency and pressure drop both decrease irreversibly (although often erratically) unless repair is possible and warranted. The onset of this period signals the end of bag life; scheduling of bag replacement is the usual response.

In this report the progressions of several woven polyester bags are followed throughout their life cycles in an attempt to isolate those variables that hasten, retard, or otherwise influence the bag aging process.

SECTION 2

CONCLUSIONS

Performance parameters, efficiency, outlet concentration, and drag, measured during two life tests carried out on woven polyester fabric filters, displayed the well known "bathtub" curve (or its inverse) behavior as a function of time. Specific cake resistance was also measured but showed no obvious time dependence. The two life tests differed: one was an accelerated test consisting of a large number of shakes per cycle; the second was a more standard cycle--the filtration and the shake-cleaning times more closely corresponded to actual field conditions. A full life cycle was completed only for the accelerated life test; however, that portion of the life cycle completed under standard conditions appeared to follow the same general pattern.

A major difference between new and used bags is that the latter contains many trapped dust particles. The quantity of trapped dust affects the performance parameters as evident from the differences in the steady-state values between bags life-tested under accelerated and standard conditions. The higher dust content of the latter resulted in not only its higher dust filtration efficiency, but also its higher pressure drop and drags. The effect of the higher dust content on bag life was not determinable from these data, however.

What the data do suggest is that dust is trapped by a fabric filter both at surface sites--the conventional dust cake--and at bulk sites. The bulk sites are defined simply as those sites retaining dust after the cleaning cycle; they are presumed to be located primarily within the fabric, but also include the residual surface dust cake not removed by the shake-cleaning. These conclusions are based on operation of shaker-cleaned filter bags used in a single-bag pilot baghouse. Mass, optical particle size, and pressure drop were the primary measurements.

Little is known about the properties and consequences of the dust trapped in the fabric. This dust can serve as a source of emitted dust, as shown by the significant outlet concentration remaining even after the inlet dust loading was dropped to zero. The dust trapped in bulk sites, which contributes to a high pressure drop, may not be the same trapped dust that enhances collection efficiency, as the hand-washing of the bag suggested. This hypothesis is just one speculative explanation, however, and is not yet a firmly established conclusion.

The intriguing possibilities uncovered by this work raise many questions, the answers to which would constitute important pieces in the fabric filtration puzzle.

SECTION 3

EXPERIMENTAL PROCEDURES

As in previous investigations of this series [Refs. 1-3], the reported experimental data originated from a laboratory baghouse consisting of a single compartment, housing one bag (Figure 1). The bag was cleaned by mechanical shaking of the bottom end, which was oscillated through a 1.75 in. stroke at 4 cycles/sec.

The fabric filters used in these experiments were woven polyester bags purchased from Lamports* to the following description:

Thread count:	76 x 65
Yarn denier:	250/250
Weave:	3 x 1 twill
Yarn type:	Continuous filament

The fabric weight was approximately 5 oz/yd^2, and the filtering area of the mounted bag was 8.5 ft^2. Flyash of mass median diameter equal to 4 μm was the only test dust used. It was fed into the air stream by a rotary screw mechanism at a constant rate of 3 grains/ft^3. The air/cloth ratio was maintained at 4 fpm. Ambient temperature in the laboratory was between 70 and 80°F, and the relative humidity in the air stream was adjusted to 50 percent for certain life tests. For other life tests the humidity was not controlled but varied with the ambient humidity. For still other supplementing short tests the humidity was varied between 23 and 70 percent.

Testing took place over a 3 year period in which bags were operated continuously for various lengths of time. During the life tests employing

*The Lamports Company, 7303 Hamilton Avenue, Cleveland, OH 44114.

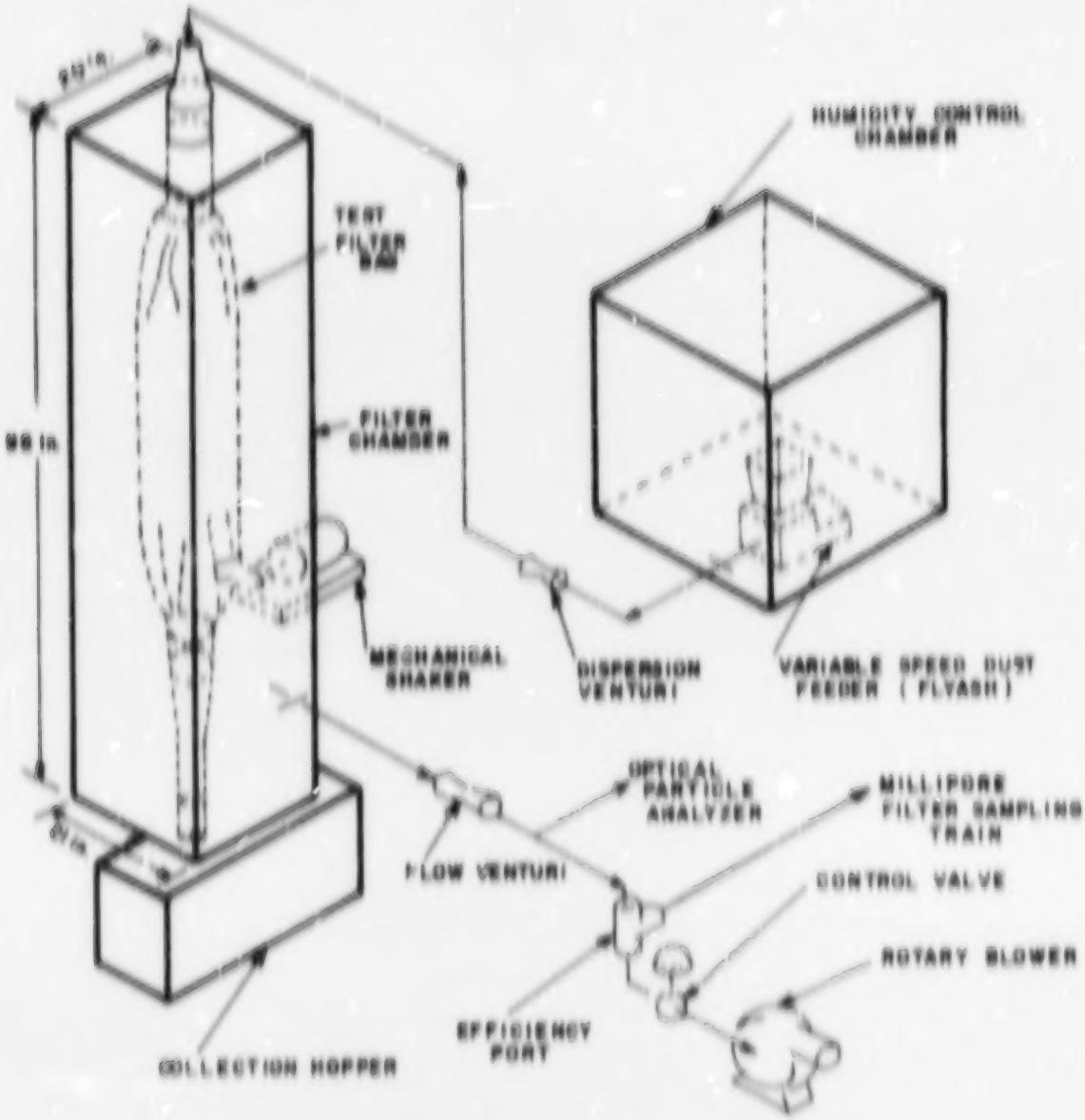


Figure 1. Test apparatus.

the standard (non-accelerated) cycle, some interruptions occurred in which the bag was removed from the test chamber and later remounted. These interruptions did influence the measured performance parameters. The accelerated life test was carried out without interruption over a 1 year period.

The measurements made routinely in evaluating the bag performance were pressure drops across the bag, relative humidity in both the inlet and outlet air flows, dust loading in both the inlet and outlet, and total flow through the system. Measurement technique was the same as previously reported [Refs. 1,2]:

1) All bag pressure drops were measured continuously using a differential pressure cell.
2) Relative humidity was sampled by a wet-bulb/dry-bulb method.
3) Dust loading in the inlet was periodically sampled by weighing the dust that was constantly and more or less uniformly added to the air flow by a rotary screw mechanism.
4) Dust loading in the outlet was determined by isokinetically sampling the flow continuously and weighing the particulate collected on a 0.45 μm Millipore* filter.
5) Size distribution of outlet dust was periodically determined by analyzing the entrained dust with an optical particle analyzer (the Climet 201)**. The sample flow for this measurement was constant through the counter; it was drawn isokinetically by adjusting the dimensions of the sampling nozzle.
6) Total flow rate through the system was monitored continuously by measuring the pressure drop across a flow rate venturi.

*Millipore Corporation, Wiggins Avenue, Bedford, MA 01730.
**Climet Instruments, P. O. Box 1165, Redlands, CA 92373.

SECTION 4

RESULTS

The major results of the bag life tests are displayed in Figures 2 and 3. These data depict the behavior of the major performance parameters throughout the life cycle of a woven dacron bag:

1) An initial "break-in" period (from zero to about 15 to 20 million shakes) during which efficiency increases, outlet concentration decreases, and drags increase.
2) A period of stabilized performance (15 to 20 million shakes up to 45 to 50 million shakes) during which all performance parameters are relatively constant (efficiency, specific cake resistance, and drags actually decrease slightly during this period; outlet concentration increases slightly).
3) The terminal period (from 45 to 50 million or more cycles) in which performance parameters (except specific cake resistance) all swing toward their initial values, completing the bath tub curve or its inverse.

Specific cake resistance decreases very slightly throughout the bag life as shown by the fitted curve in the top plot of Figure 3. The correlation coefficient (r^2) for this curve is on the order of 0.01, meaning that the value of K_2 is independent of the number of shakes. The time required to establish a constant change of drag per incremental dust cake loading changes with time as sketched in Figure 4.

All the curves traced in Figures 2 and 3 are least squares fits to the data over all or a portion of the bag life. A better fit to the efficiency and outlet concentration data results when the steady-state period is divided in two, as shown by the dashed curves in Figure 2.

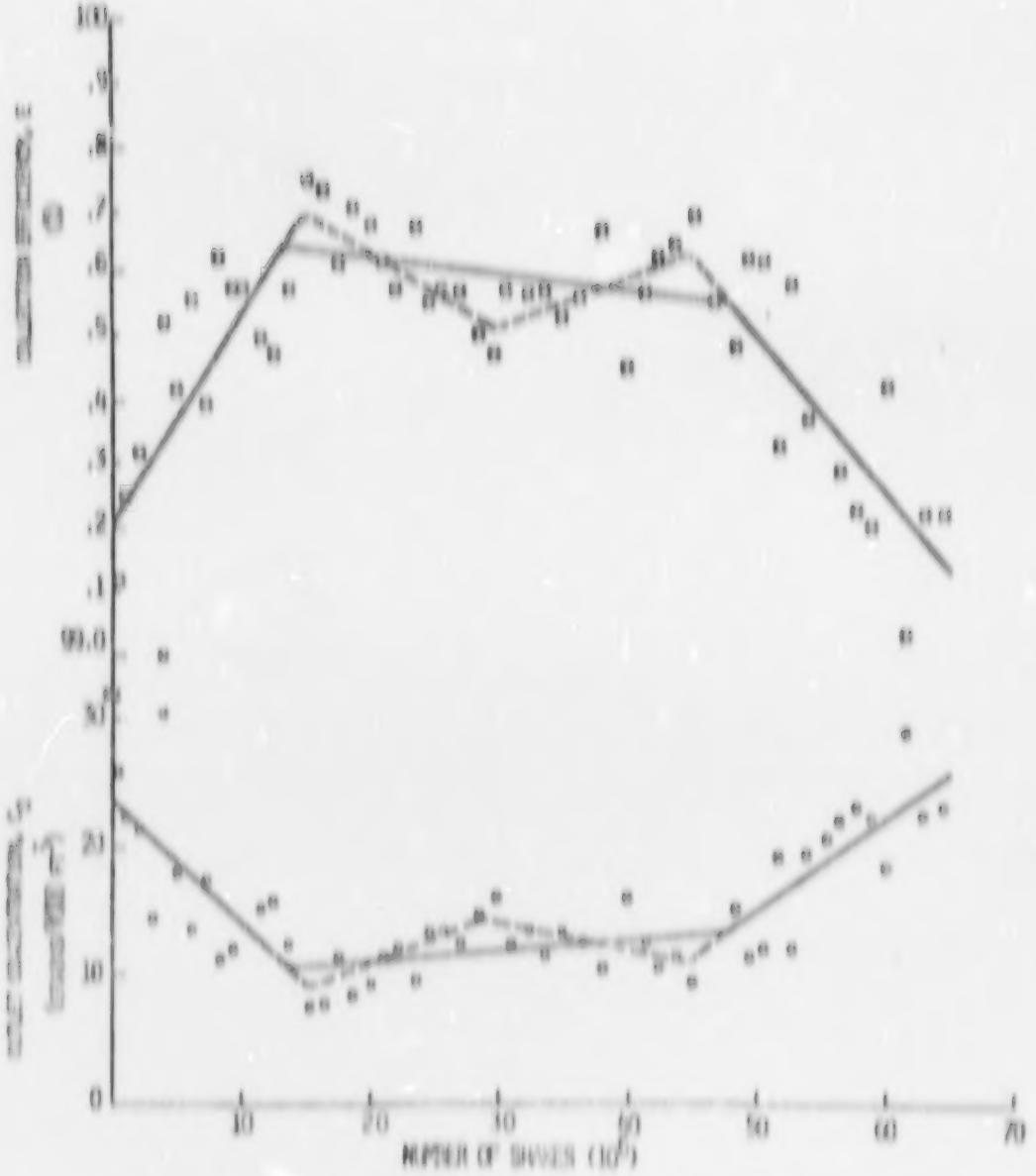


Figure 2. Performance data under accelerated life test: mass collection efficiency and outlet concentration.

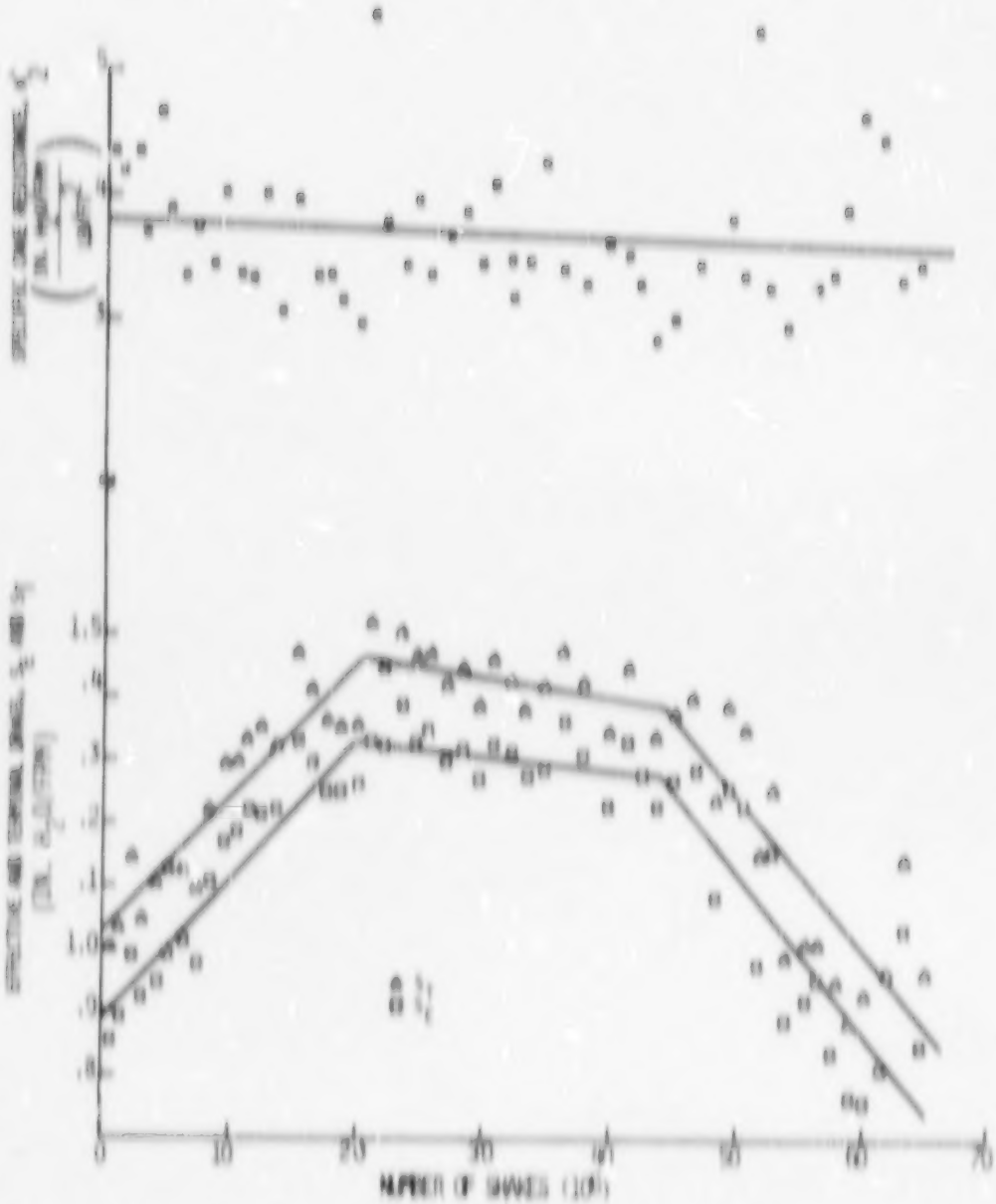
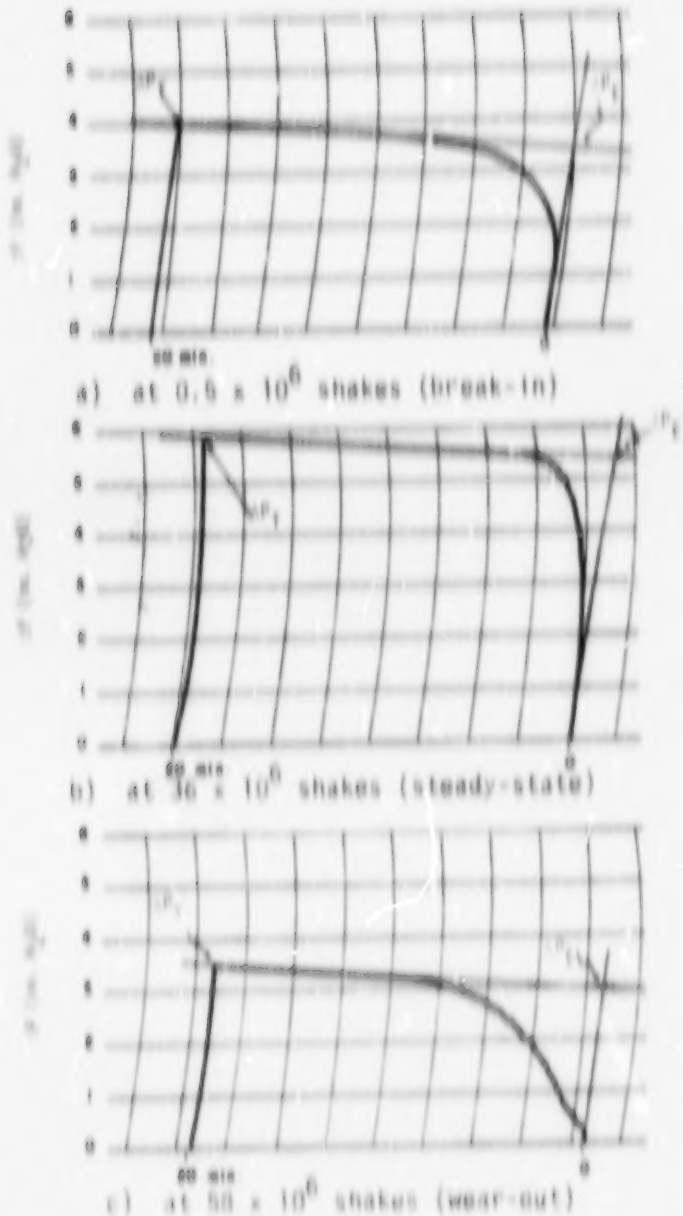


Figure 3. Performance data under accelerated life test: specific cake resistance and drags.



a) at 0.5 x 10^6 shakes (break-in)

b) at 30 x 10^6 shakes (steady-state)

c) at 58 x 10^6 shakes (wear-out)

Figure 4. Traces of pressure drop across the bag during filtration.

The data of Figures 2 and 3 are based on accelerated testing (i.e., the test cycle used consisted of time increments differing from those of the "standard" cycle):

Accelerated shake cycle	2 minutes	1 minute	15 minutes
	Filtration	Delay	Shake Cleaning (4 shakes/sec)
Standard cycle	20 minutes	1 minute	2 minutes

At a shake frequency of 4 shakes/sec the accelerated shake cycle consists of 3600 shakes/cycle rather than the 480 shakes of the standard cycle. Thus the effects of mechanical shaking could be observed in much shorter calendar times than if using the standard cycle.

All measurements made during accelerated testing, however, were made using the standard cycle. The procedure was to shift to the standard cycle and, after operating for several cycles with the standard cycle, use the full 20 minute filtration portion of the cycle to collect a mass sample for efficiency calculations.

While the modified cycle does have the merit of accelerating the number of shakes accumulated per unit of test time, it departs from realistic conditions in that the total dust passing through the fabric and the average dust loading to which the fabric is exposed are lower than normally encountered in a typical field installation. Not only are the number of cleaning shakes greater during the accelerated tests but the filtration time is a factor of 10 less than during the standard cycle. The combination of accelerated cleaning and reduced dust filtration could be expected to change the aging properties of the bag.

Performance measurements generated by a woven polyester bag operating on the standard cycle are plotted as a function of time in Figures 5 and 6. The abscissa in these plots is number of cycles. Ten thousand cycles represent 4.5×10^6 total shakes, a relatively small number on the scales of Figures 2 and 3. Total operating time (2.5 standard cycles per hour) was a little over 4567 hours; but, since the testing

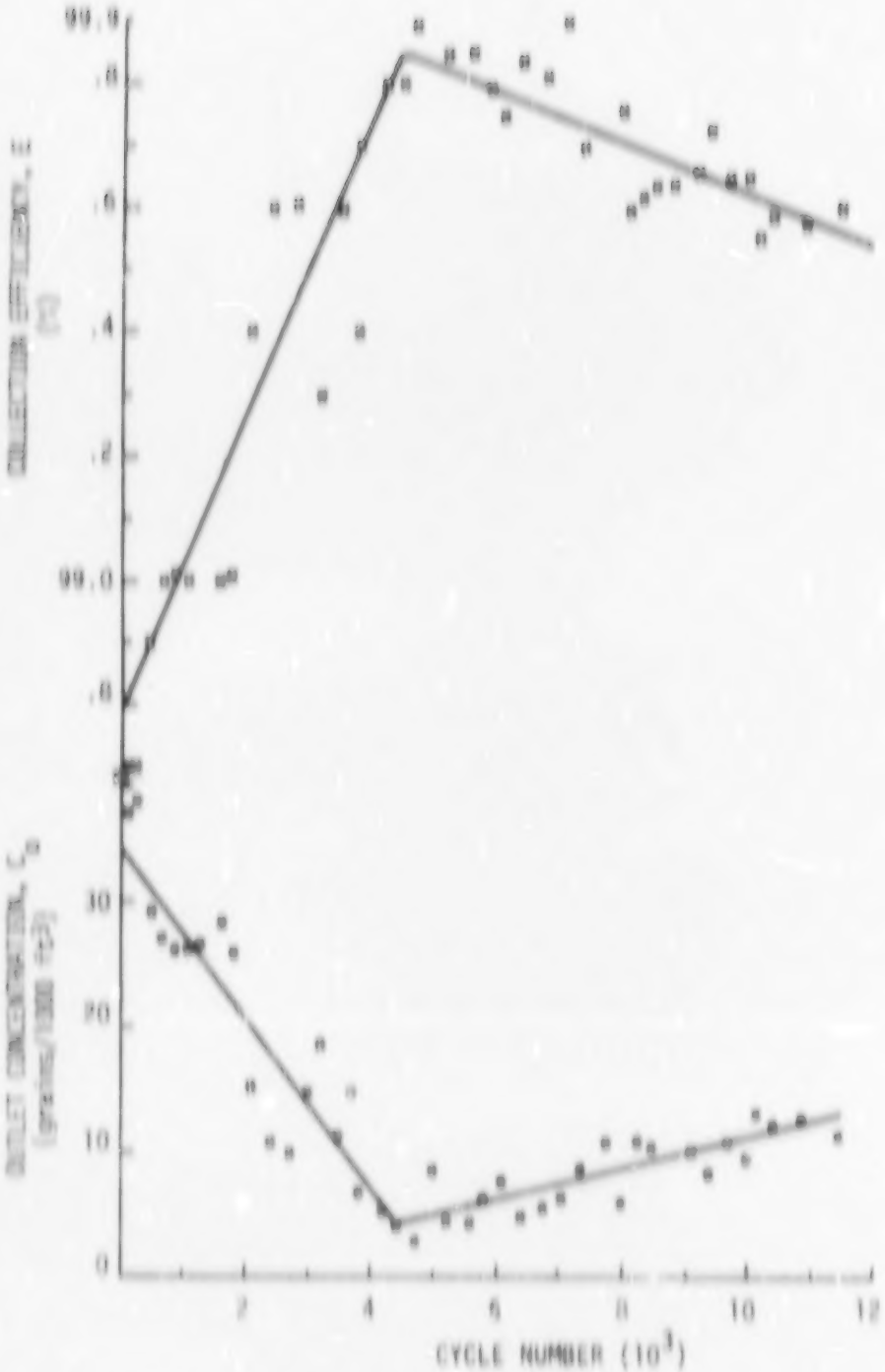


Figure 5. Bag performance data under standard conditions: mass collection efficiency and outlet concentration.

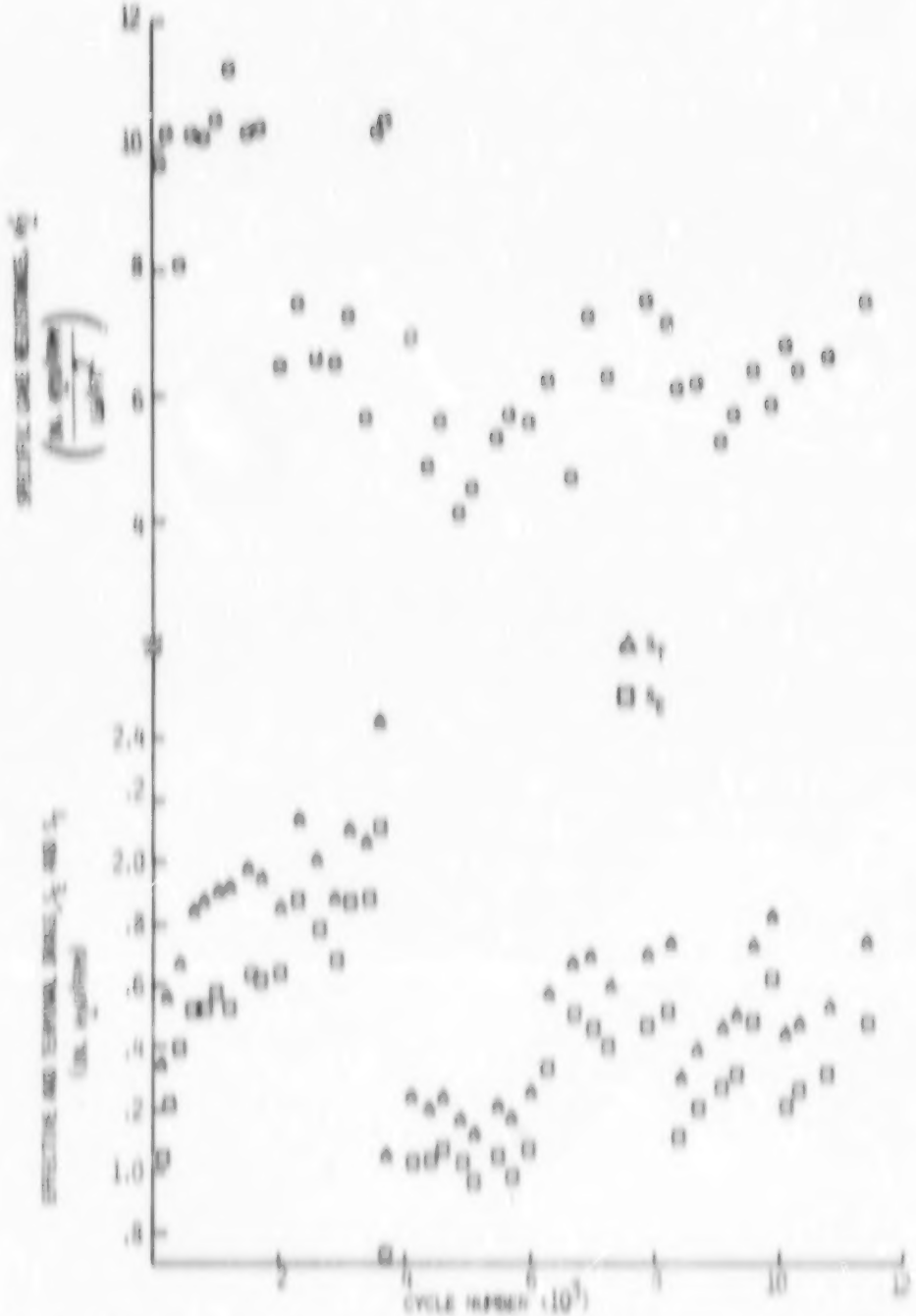


Figure 6. Bag performance data under standard conditions: specific cake resistance and drags.

was not continuous, it took over a year to complete. Some of the discontinuities in the data plots result from interruptions in operating time.

Four known or suspected sources of breaks in the data exist:

1) At about cycle 2000 a leak was discovered in the baghouse which probably caused feed rate errors. Discontinuities in the plots of E, C_0 (Figure 5) and K_D' (Figure 4) resulted from this source. Drags, being only indirectly related to dust feed rate, do not reflect a major discontinuity (Figure 6).

2) After cycle 3730 the pressure drop across the bag exceeded 10 in. of water, an unacceptably high value. The bag was removed, hand washed in soap and water, dried, and remounted. A major discontinuity appears in the drag plot and anomalously high readings of K_D' occurred temporarily. C_0 and E do not show significant breaks.

3) After cycle 8380, the bag was again removed for cleaning. This time it was not washed but merely shaken by hand and then remounted. A 2-1/2 month delay occurred before the next test data. An obvious discontinuity exists in the drag plots; less obvious discontinuities may exist for the other variables.

4) After cycle 9981 a 4 month break in the test program took place. The most noticeable effect of this interruption is seen on the drag plot.

The increase in drags around cycle 6200 is anomalous. A shift in drag comparable to those occurring at cycles 8380 and 9981 is evident at cycle 6200 in figure 6, but no ready explanation exists for it.

More data exist than are plotted in figures 5 and 6. For clarity these plots show only every fourth datum point up to cycle 5507. Beyond this cycle the plots include every other datum point. The curves shown in figure 5, however, have been fitted by the least squares method to all the data; clearly the omission of over half the data points from the plots does not change the reasonable fit.

Aside from the discontinuities evident in Figure 6 (attributable, as discussed previously, to interruptions, errors, special procedures, or unknown causes), standard-cycle bag performance parameters appear to be following the same general aging pattern as delineated by the time dependence of the accelerated-test-cycle performance parameters and as plotted in Figures 2 and 3:

1) The efficiency curve (Figure 5) shows a sharp initial rise and the C_0 curve (Figure 5), a rapid initial decline--both curves reaching an extremum at about cycle 4400 and subsequently undergoing a gradual reversal in values. This behavior correlates with the first half of the data plotted in Figure 2, the corresponding plots for accelerated life tests (as shown by the dashed curves of Figure 2). In Figure 2 the extrema occur at about 15×10^6 shakes with the reversal extending to about 30×10^6 shakes. By comparing Figures 2 and 5, the life cycle depicted in Figure 5 can be estimated to be about half that of the full life cycle shown in Figure 2. The influence of the larger average dust loading characteristic of the standard cycle reflects itself in higher efficiencies and lower outlet concentrations for that cycle (Figure 5). The increased dust loading, in combination with reduced shake cleaning, apparently produces an increased residual dust cake in or on the fabric which not only improves filtration efficiency, but also causes higher drags as discussed next.

2) The drags measured under the standard cycle (Figure 6) also show a rapid initial buildup like those observed with the accelerated cycle (Figure 3). Specific cake resistance in both cycles shows no marked trend (assuming the K_2 data for cycles less than cycle 2000 (Figure 6) are neglected because of the feed rate errors discussed previously [see Item 1, p. 14]). The higher average dust load of the standard cycle (2 min dust feed/accelerated cycle vs. 20 min dust feed/standard cycle) produced intolerably high pressure drops across the bag

(the final pressure drop exceeded 10 in. of water) which led to an unscheduled bag washing after cycle 3730. This washing succeeded in reducing drags without penalizing bag efficiency--a very desirable response, more fully discussed in Section 5. Following the discontinuity at cycle 3730, attributable to bag washing, drags increase again but level off below the high values encountered just before the washing. Several smaller discontinuities, attributable to test interruptions, are also evident.

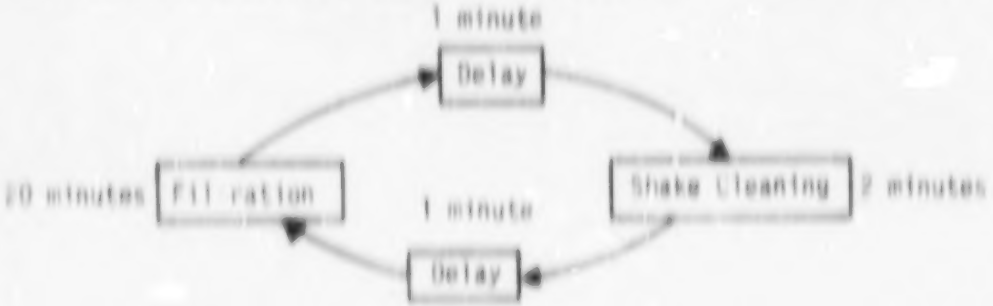
The effect of the higher average dust load/reduced shake-cleaning is to cause higher values of both K_2 and the two drags, as can be seen by comparing the values plotted in Figures 3 and 6. The life cycle of the bag, readily apparent in the drag data of Figure 3, is only incompletely revealed in Figure 6, being too brief in duration to show the entire cycle and being obscured by various pronounced discontinuities.

Total dust load--the time-integrated dust feed--and shake-cleaning together produce significant differences in aging characteristics of performance parameters of these woven polyester fabric filters. A "complete" life cycle is assumed to be that portrayed in Figures 2 and 3, based on data recorded during the accelerated life test. An incomplete life cycle is represented by data plotted in Figures 5 and 6, based on data taken during the standard operating cycle. By comparing the initial rise time of the aging curves for efficiency and C_0 (and consistent with the other performance data as well) 15×10^6 shakes of the accelerated cycle can be equated to about 4700 cycles of the standard cycle (the maximum value of collection efficiency in Figure 2 is at 15×10^6 shakes; that in Figure 5 is at 4700 cycles). This crude comparison implies a life acceleration factor of about 6.5 for the accelerated test cycle over the standard cycle (4700 cycles x 480 shakes/cycle = 2.3×10^6 shakes), only slightly less than the acceleration factor based solely on the ratio of the number of shakes (3600/480 = 7.5). This reasonable agreement implies that the accelerated test cycle is a valid method of generating bag life data in spite of the low average dust loading.

More compelling in suggesting that dust filtration time and cleaning parameters play an important role in fabric filtration are their influence upon the steady-state values of all performance parameters during the period of stable bag performance (the flat portion of the curves in Figures 2 and 5). Comparing Figures 2 and 3 with Figures 5 and 6 shows that the accelerated test cycle in the steady-state period displays lower efficiency, drag, and specific cake resistance, but higher outlet concentration. These observations imply that more dust clings to the surface of the fabric or is imbedded within it during the standard cycle than during the accelerated test cycle--even after the steady-state period has been reached.

To further investigate the presence of this dust and its location on or within the fabric, additional data were gathered, using the optical particle counter. All of those data were taken with the basic time sequences of the standard cycle rather than those of the accelerated test cycle. Often, however, some modification of one or more of the time sequences was used.

As discussed previously the standard cycle is:



The optical counter measures the size distribution of particles in the outlet during the 20 minute filtration cycle. Figure 7 is a typical plot of the optically detected particles in the outlet, using a woven polyester bag to filter flyash. This dust/fabric system displays the commonly observed dust cake filtration properties [Ref. 4]. At the beginning of the filtration period, particle penetration is high (the peak occurring at 2 minutes in Figure 7 may be an artifact of the

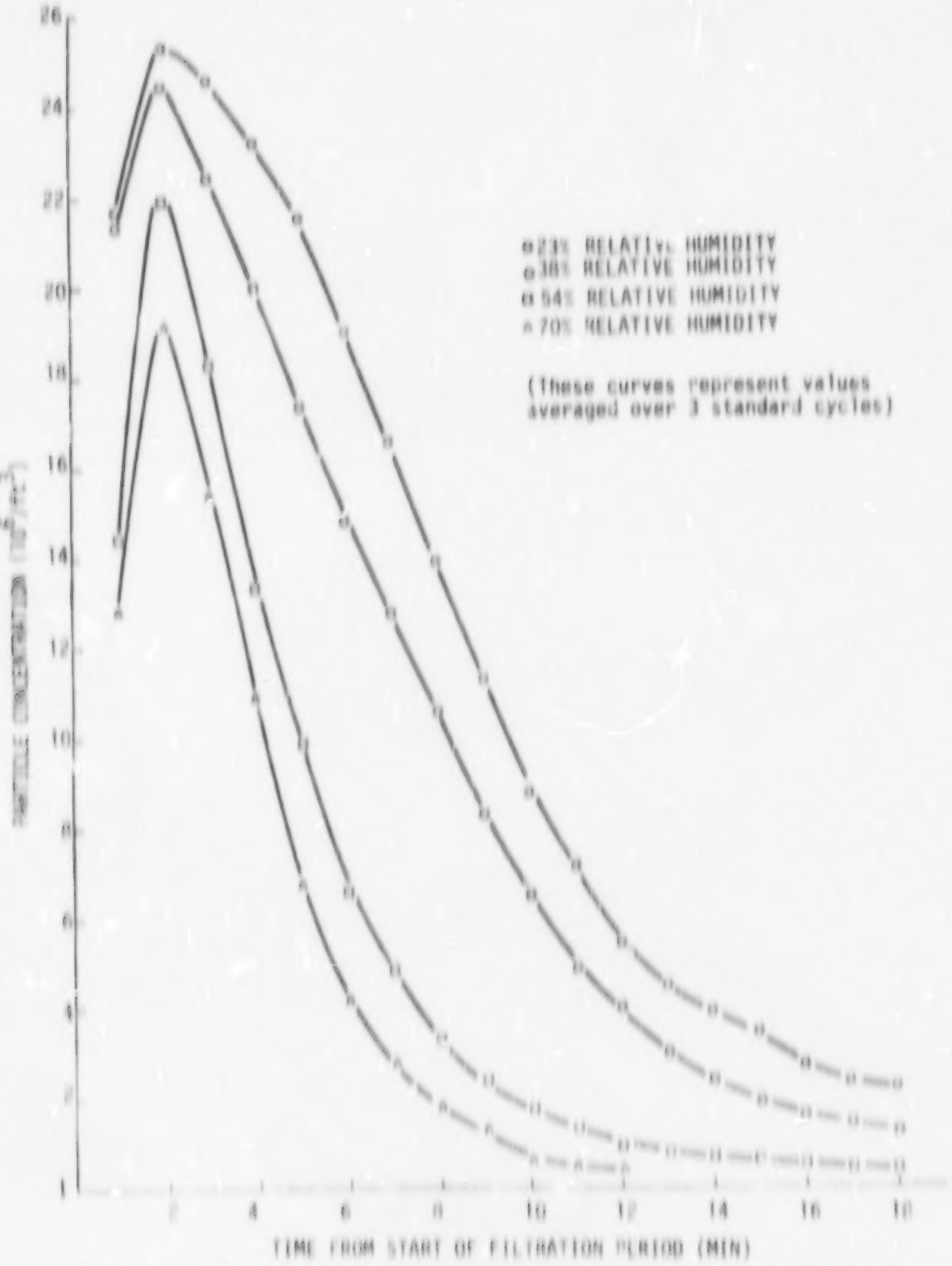

23% RELATIVE HUMIDITY
38% RELATIVE HUMIDITY
54% RELATIVE HUMIDITY
70% RELATIVE HUMIDITY
(these curves represent values averaged over 3 standard cycles)
TIME FROM START OF FILTRATION PERIOD (MIN)

Figure 7. Total number density of particles (0.3 μm and above) in the outlet during filtration.

measuring technique--the blower starts at time zero of the filtration period so that any delay in particle penetration and transport through the baghouse and its feeder lines (Figure 1) could manifest itself a lower particle particle penetration during the first samplings of the filtration period). As the dust cake builds up during the filtration period, particle penetration decreases rapidly because of particle capture by the dust cake. The added pressure drop across the dust cake/fabric filter composite necessitates a shaker-cleaning during which much of the dust cake is removed. When the next filtration cycle begins, pressure drop across the bag is low but the particle penetration is again high. As the dust cake rebuilds, these parameters change as before--pressure drop increases and particle penetration decreases--until the cycle must be repeated again, as dictated by a predetermined maximum pressure drop in a field installation. In the standard cycle employed in the work reported here, the duration of the filtration cycle is held fixed at a constant 20 minutes rather than being determined by the pressure drop.

The data in Figure 7 reflect a humidity dependence often seen in the fabric filtration of flyash--a reduction in mass penetration (C_0) with increasing relative humidity [Ref. 5]. Figure 7 shows that the number density of the penetrating flyash particles (0.3 μm and above) also follows this pattern. The optical counter data to be presented in this paper are low humidity data (23 percent relative humidity) simply because these number densities are the largest. Similar behavior occurs at other relative humidities; relative humidity, while obviously influencing particle penetration, is assumed not to alter the basic interactions in any major role.

The first modification of the standard cycle investigated was a reduction in the shake-cleaning time and hence the total number of shakes. Figure 8 shows the effect of shortening the cleaning cycle on bag pressure drop. The pressure drops vary inversely with the log of the total number of shakes in the cycle. Figure 9 shows that the total number of particles measured by the optical detector decreases with decreasing number of shakes and, more importantly, that the time required to re-establish high efficiency filtering also decreases with

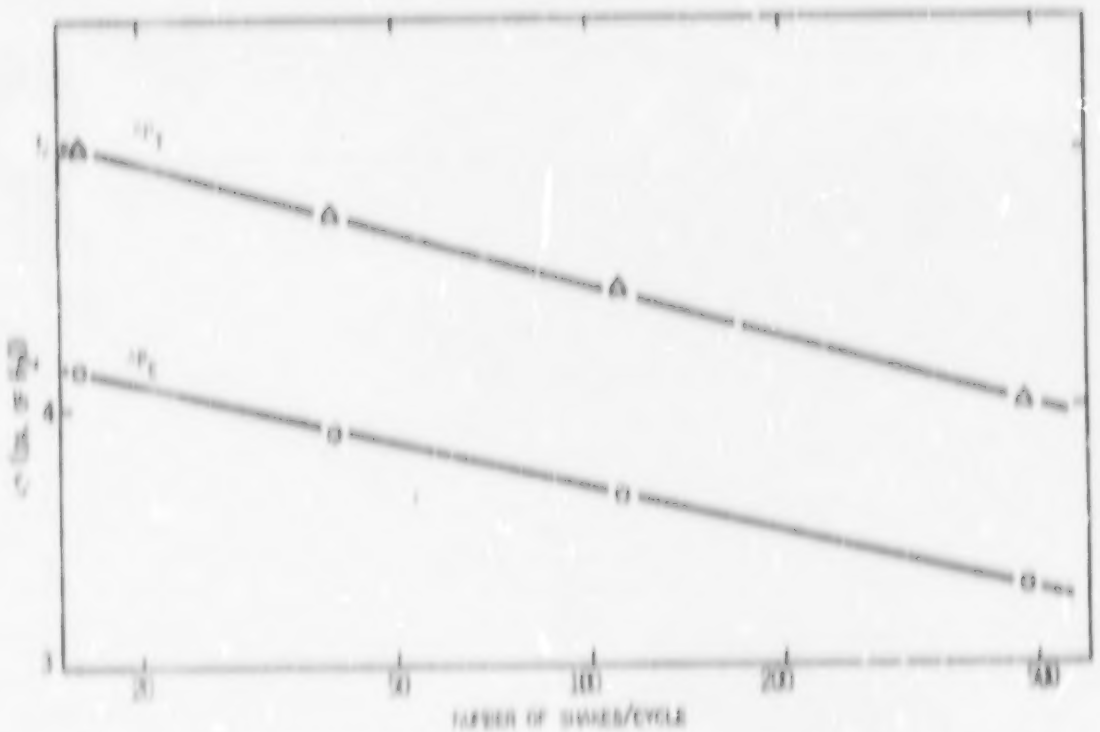


Figure 8. Relationship between bag pressure drops and length of shake-cleaning period.

decreasing number of shakes. Not surprisingly, the net effect of reducing the number of cleaning shakes per cycle is to leave a dirtier bag in the sense that more dust remains in or on the bag as detected by the higher pressure drops and the reduced particle penetration during the filtration cycle. The assumption is that both these changes are attributable to less complete removal of the dust from the bag.

These same changes in performance take place during the initial break-in period of a bag. Pressure drops increase with succeeding cycles, as plotted in Figures 3 and 6, and particle penetration through the bag decreases, as shown by the C_0 plots of Figures 2 and 5. The optical counter data also detect less particle penetration after, say 64 cycles, than after 5 cycles (Figure 10). The conclusion is that, during the initial break-in period, the bag becomes dirtier by receiving and retaining more particles than it releases--the bag acts as a particle sink. Figure 10 illustrates the conclusion well known to baghouse operators that the bag accumulates a residual dust holding during the

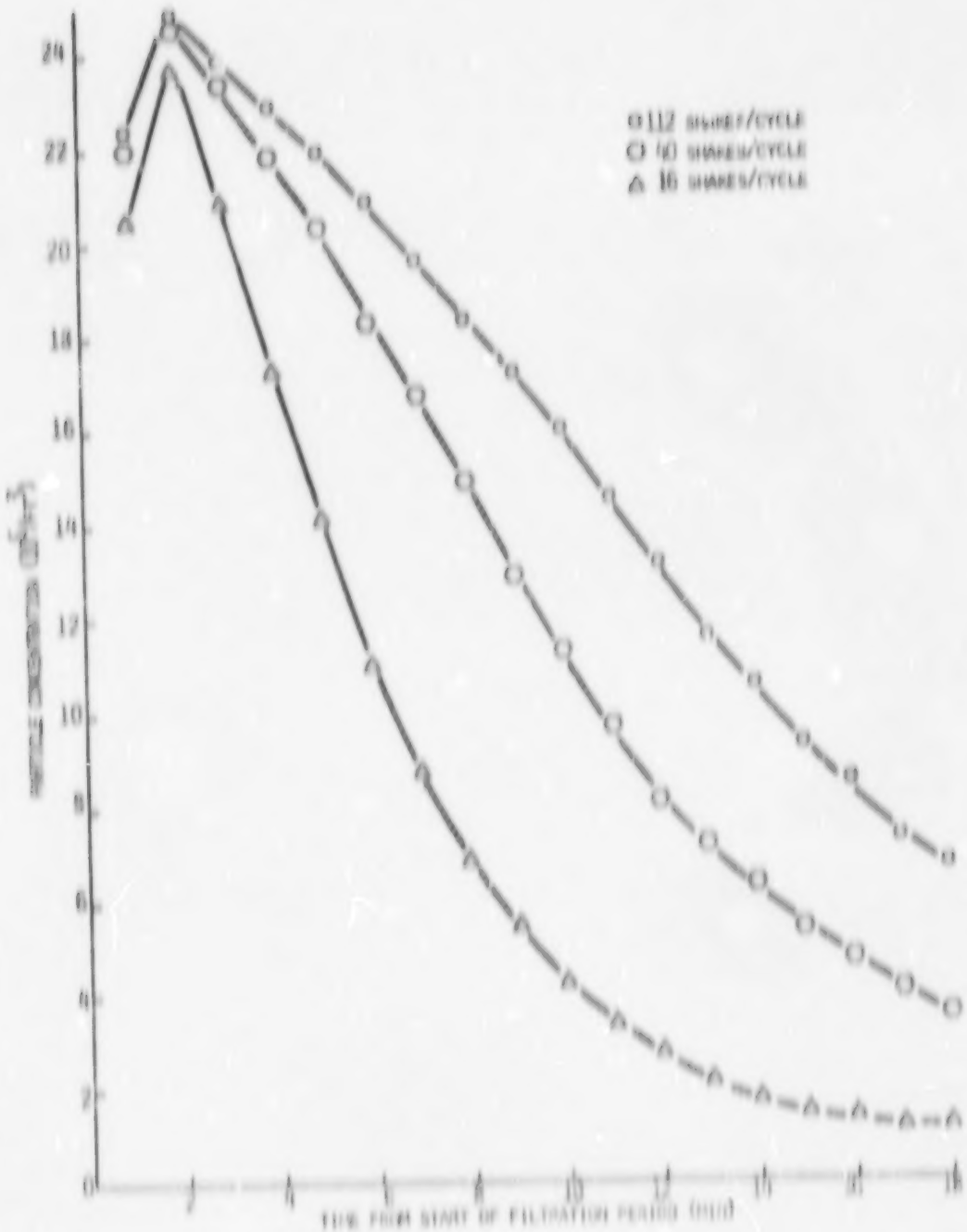


Figure 9. The influence of shake cleaning upon the number density of outlet particles (0.3 μm and above).

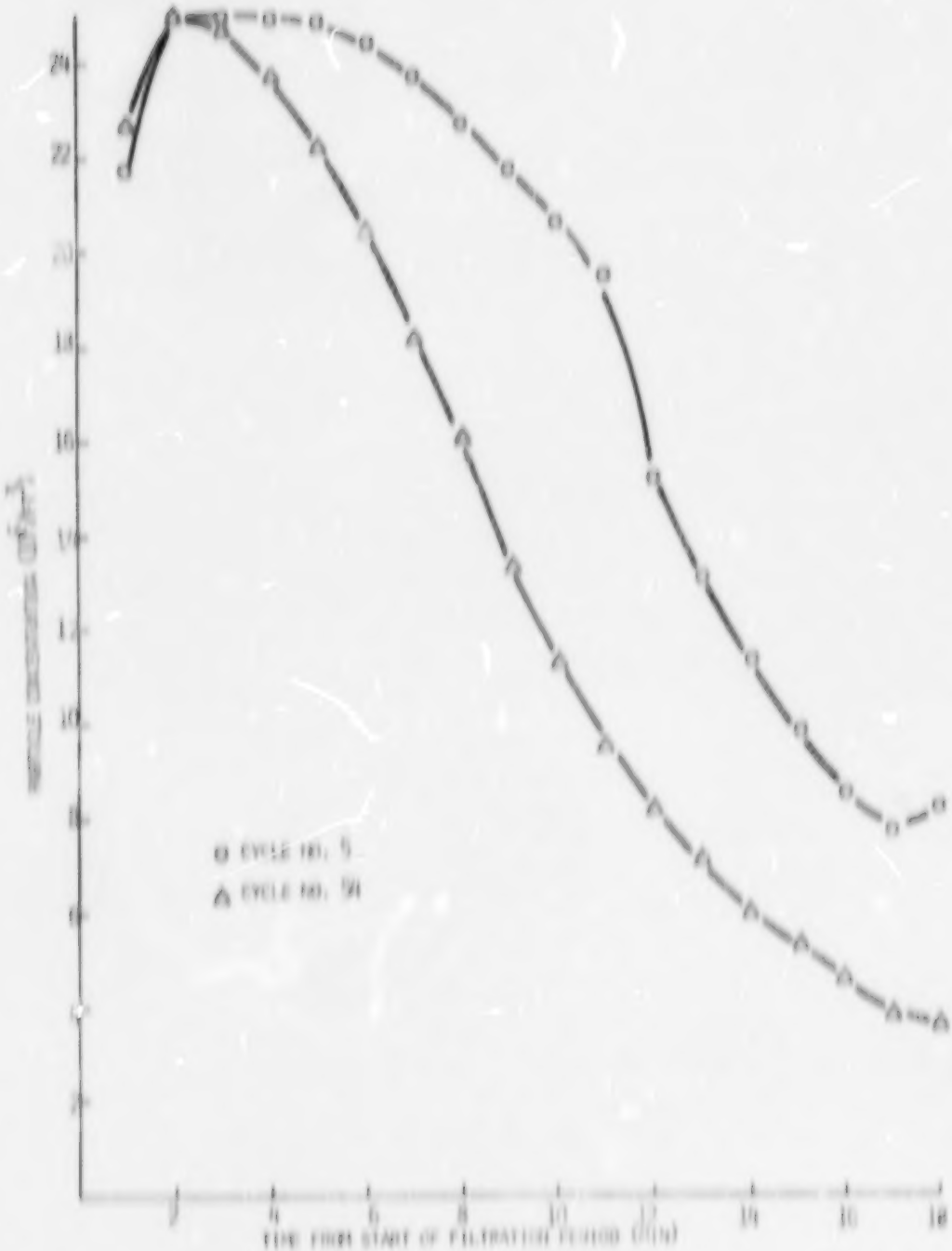


Figure 10. Aging as reflected in the number density of outlet particles (0.3 μm and above).

initial bag break-in period. It acts as a sink by retaining more particles than it releases until reaching a steady-state condition.

During its stable period, the bag presumably operates in a steady state whereby the total number of particles received per cycle equals the total number lost. In the steady-state period, however, the bag is more than just a fabric; it is a fabric loaded or saturated with dust particles. Moreover, these added dust particles play a useful role as evidenced by the improved filtration efficiency of the bag in steady state and the reduced particle penetration through it.

Questions now arise regarding those dust particles acquired by the fabric filter during its break-in period:

1) Where are they?
2) How are they held?
3) In what kinetic processes do they participate?
4) What are their population densities?
5) What influences their numbers, sizes, and other properties?

The results already reported in this paper provide some answers. In addition, further procedural modifications were undertaken to learn more about their properties.

One modification consisted of stopping the dust feed partway through the filtration cycle, but continuing to monitor the size distribution of dust in the outlet (with the optical counter). The classical particle capture processes (interception, inertial impaction, diffusion [Ref. 6]) all assume straight-through particle penetration--the particle is either caught or it isn't; no allowance is made for multi-stepped delayed penetration. If these classical mechanisms are all that influence penetration, then the dust concentration in the outlet should drop to zero as soon as the inlet dust loading is shifted to zero. What actually happens is shown in Figure 11--the dust loading drops off gradually after the dust feed is stopped. The data presented in Figure 11 compare the dust in the outlet (measured during the fourth standard measuring cycle at 23 percent relative humidity) with that measured during the first measuring cycle at that humidity (all bags were stablized at a given humidity by running the standard cycles for at least 24 hours prior to making any measurements; the fourth standard measuring cycle is

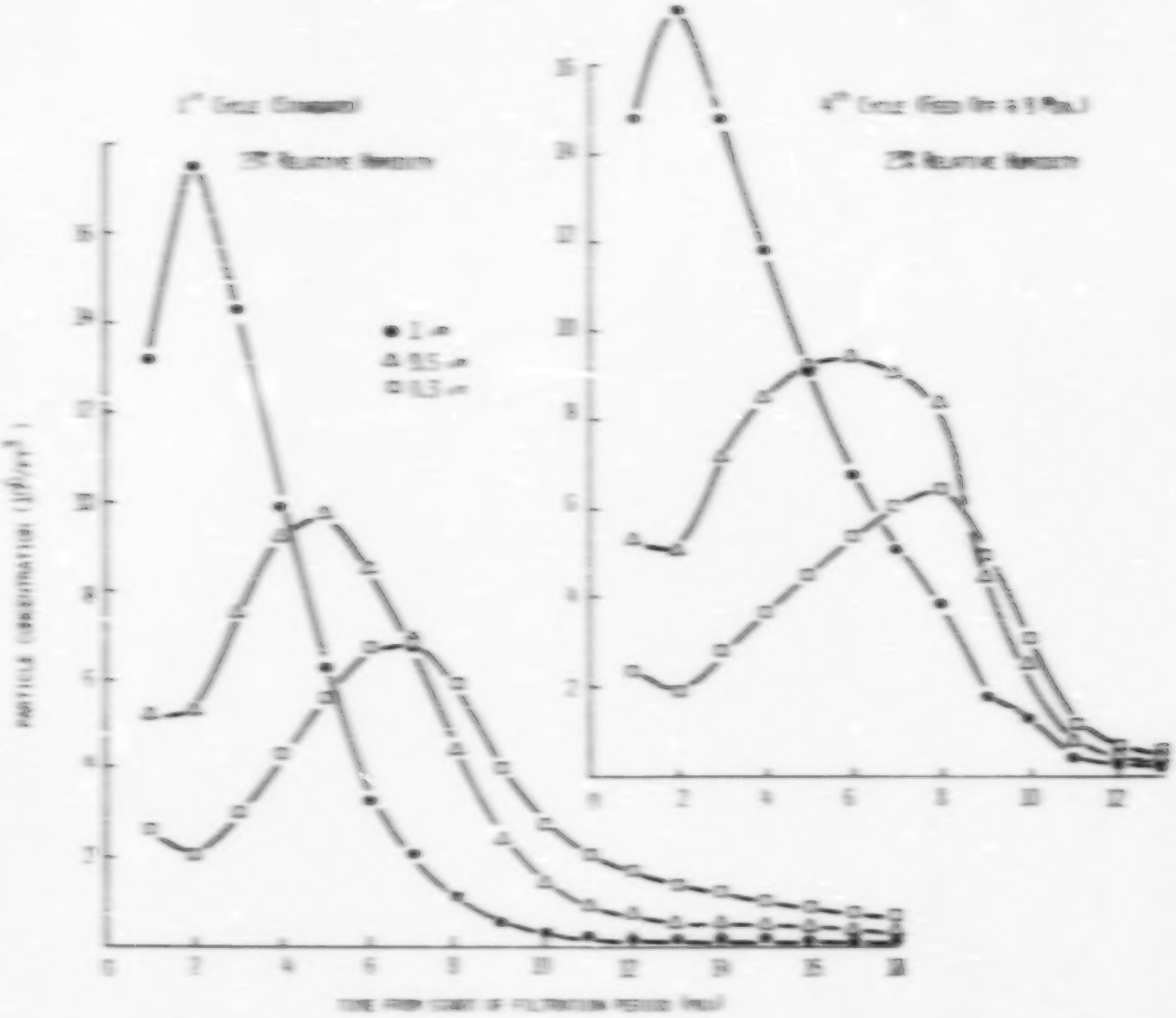


Figure 11. The effect of eliminating the dust feed upon the number density of outlet particles.

the fourth cycle of a test sequence). During the 20 minute filtration period of the fourth cycle, the dust feed was stopped 8 minutes into the period. The outlet concentration varied as plotted in Figure 11 for the three most populous dust size-groups. Some drop-off in dust concentration is evident after the dust feed stops (fourth cycle), but the time dependence of the outlet dust concentration is not markedly different during the first and fourth cycles.

After completion of the fourth cycle, the dust feed was returned to normal for the fifth cycle, but was turned off afterwards and left off for all succeeding cycles. Total (the sum of all size groupings) particle concentrations as measured by the optical detector are plotted in Figures 12 and 13. Table 1 summarizes the conditions under which the filtration step of each cycle was conducted. Curves for cycles 1, 2, 3 and the first 8 minutes of cycle 4 (Figure 12), illustrate experimental variation typical of the optical counter data. These curves are taken under identical conditions but show particle penetration profiles that vary as illustrated.

Table 1. DUST PENETRATION SERIES, WOVEN POLYESTER BAG (LAMPORTS STYLE NO. 4027-SHT) AT 23% RELATIVE HUMIDITY

Cycle No.	Conditions
1	Standard*
2	"
3	"
4	" (dust feed OFF at 8 minutes)
5	"
6	" (dust feed OFF)
7	"
8	"
12	"
17	"

*Air/cloth ratio = 4 fpm; dust feed = 3 gr/ft^3).

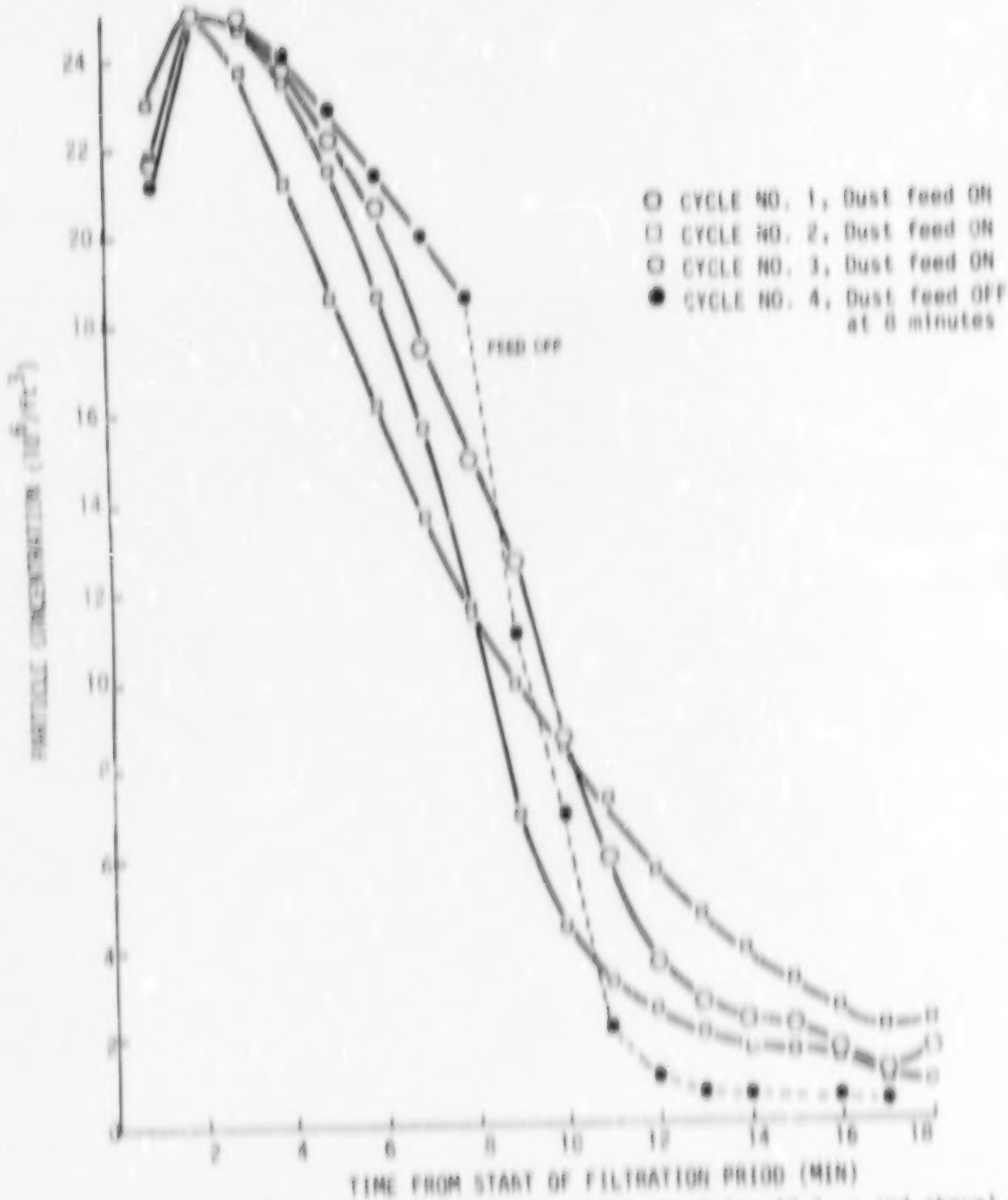


Figure 12. Total number density of outlet particles (0.3 μm and above) during sequential cycles 1-4.

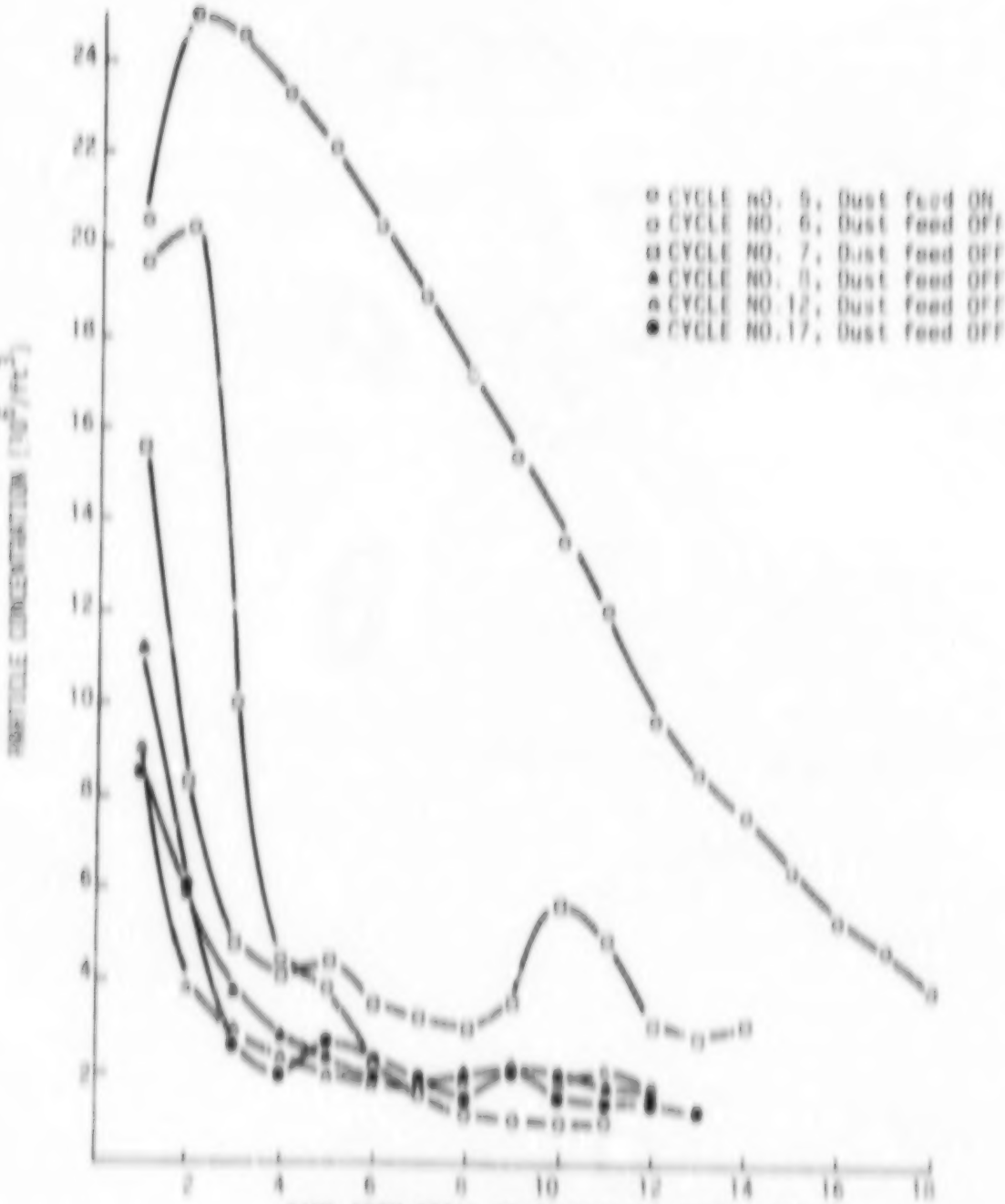

CYCLE NO. 5, Dust feed ON
CYCLE NO. 6, Dust feed OFF
CYCLE NO. 7, Dust feed OFF
CYCLE NO. 8, Dust feed OFF
CYCLE NO.12, Dust feed OFF
CYCLE NO.17, Dust feed OFF
PARTICLE CONCENTRATION (10^6/m^3)
TIME FROM START OF FILTRATION PERIOD (MIN)

Figure 13. Total number density of outlet particles (0.3 μm and above) during sequential cycles 5-8, 12, and 17.

Clearly dust concentrations, significantly above background levels, continue to exist in the outlet of the bag, even though the inlet dust feed has been stopped. As in standard cycles, dust concentrations are greatest at the start of each new cycle and subsequently decline to low values before the cleaning step. At the start of the next filtration period, however, dust concentrations have built back up to much higher values than at the termination of the previous filtration period. This recovery occurs even though no dust feed has taken place during the cycle.

This same behavior is presented somewhat differently in Figures 14 and 15. Figure 14 is simply a bar graph plot showing the outlet dust concentrations during each of the first 6 minutes of the sixth cycle. This cycle is the first cycle having no dust feed at all (table 1). The data labelled 1 minute are compared with the 1 minute data from subsequent cycles in figure 15. Dust concentrations are decreasing as the bag cycles through the sequences with no dust feed. Note, however, that the minute 1 data of cycle 7 (Figure 15) show much greater dust concentrations than the minute 6 data of cycle 6 (Figure 14). So do the minute 1 data of cycles 8, 12, and 17 (Figure 15).

The implication is that a dust source remains in the baghouse even after the source of external dust feed is removed. Furthermore the hypothesis is that this dust source is the dust-loaded bag itself which emits a continually declining quantity of the dust trapped within it to each succeeding period of air flow. Bag flexure during the stopping and starting of the air flow probably helps loosen some of the trapped dust.

The optical counter data presented in figures 11 through 15 have been taken with air flow at 23 percent relative humidity. At higher relative humidity--54 to 78 percent--the dust concentrations are not as great but they exhibit the same general behavior. Relative populations in the size classes may shift with changing relative humidity, however.

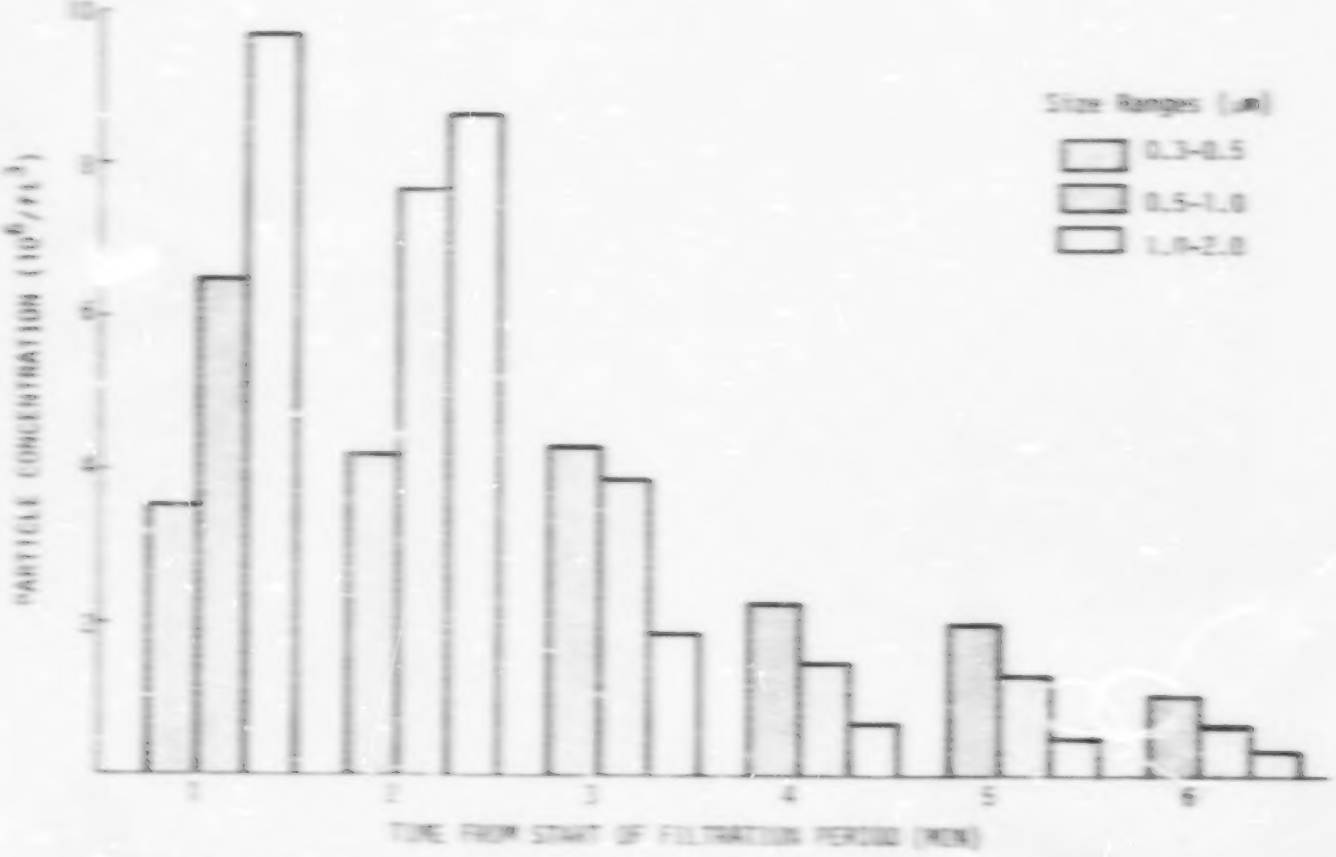


Figure 14. Size distribution of particles at each of the first 6 minutes of the first cycle with no duct heat (cycle 6, Table 1).

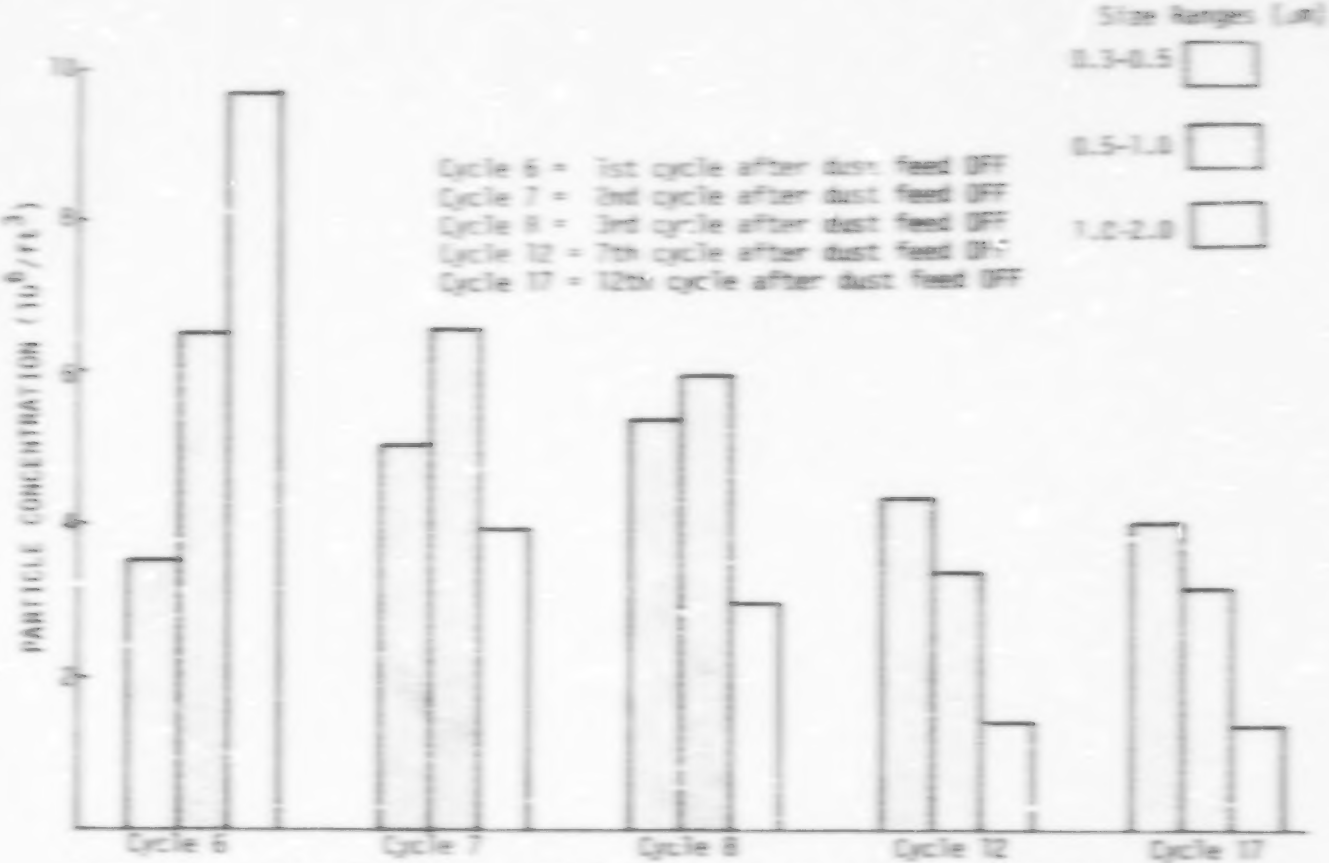

Size Ranges (μm)
0.3-0.5
0.5-1.0
1.0-2.0
Cycle 6 = 1st cycle after dust feed OFF
Cycle 7 = 2nd cycle after dust feed OFF
Cycle 8 = 3rd cycle after dust feed OFF
Cycle 12 = 7th cycle after dust feed OFF
Cycle 17 = 12th cycle after dust feed OFF
PARTICLE CONCENTRATION (10^6/ft^3)
Cycle 6
Cycle 7
Cycle 8
Cycle 12
Cycle 17

Figure 15. Size distribution of particles in the first minute of various cycles following the termination of dust feed.

SECTION 5

DISCUSSION

A used fabric filter is not quite the same as a new fabric filter. The used fabric filter is a more efficient filter but is also less permeable to air flow--it presents a higher impedance to air flow than the new fabric filter.

One obvious explanation--an explanation consistent with the observations reported here--is that the used filter is a dust-saturated, or at least a dust-loaded, fabric. While the fiber density and number do not change from those of the new filter, the used filter contains added dust particles occupying either (or both) surface sites or bulk positions within the fabric that are not occupied in the new filter. As reported elsewhere, the added dust does not directly alter the mechanical strength of the fabric [Ref. 7], although certain dusts can hasten wear because of their abrasive properties. Gas permeability of a used filter, however, is reduced because the dust fills otherwise unoccupied voids.

The interaction between a dust and a fabric filter depend on the properties of both the dust and the fabric. The following discussion interprets primarily the observations reported in this paper; certain of the conclusions could be restricted to just the flyash/polyester system investigated here.

The picture of the dust/fabric interaction developed in the course of these investigations is one in which dust penetrates the fabric filter by both straight-through (no time delay) passages and delayed multi-stepped paths, perhaps analogous to the seepage and pinhole plug mechanisms identified by Leith et al. in studying mass transport through dust cake/fabric composite structures [Ref.8]. The only distinction justified by the observations reported here is that between immediate penetratio

(no time delay) and delayed penetration. Presumably the former corresponds to a straight-through trajectory whereby the particle is not captured by any fiber of either the fabric or the dust cake. The delayed penetration is that component of penetration that "works" its way through the dust cake and fabric to emerge on the clean air side of the filter at a later time. Germane to the concept of a delayed component of particle penetration is the assumption of a multistep trajectory whereby a particle moves through the filter in a series of short hops from one metastable site to another. The concept implies a sequence of capture and release processes governing the transport of dust particles through the filter.

The previous discussion suggests that dust particles can be trapped or retained by a fabric filter at one of two general sites:

1) a surface site, or

2) an interior bulk site.

Surface sites make up the dust cake. Interior bulk sites extend from one surface of the fabric through to the opposite surface and consist of metastable dust-particle-trapping sites which fill when exposed to dust flow. The filling of the bulk sites takes place during the bag break-in period. Saturation of these sites or attainment of their maximum steady-state values of occupancy marks the beginning of the bag's steady-state period.

Surface sites make up that portion of the dust cake which is removed by the shake-cleaning of each cycle. Bulk sites are those occupied by the dust not removed by the shake-cleaning. Some bulk sites may actually be in the vicinity of the fabric surface but, because of their relative permanence, they are called bulk sites by the preceding definition.

The influence of surface sites (dust cake) upon bag performance parameters is well known [Refs.5,6]. Less understood is the role of the bulk sites. The performance data gathered here show that their influence can be substantial, too. Intracycle variations of performance parameters are attributable to dust cake; similarly, at least some of the long term

behavior of these parameters is attributable to dust in bulk sites. The break-in period has been described as the time required to reach a steady state in which the dust being trapped at bulk sites just equals the dust being released. For operation at high dust loadings and long filtration periods, the steady state requires a higher occupancy of bulk sites. Hence, the dust trapped in the fabric filter is greater when operating with the standard cycle (Figure 5) than with the accelerated cycle (Figure 2), as reflected in the efficiencies and outlet concentrations of the two cycles as well as in the drags and specific cake resistance (Figures 3 and 6).

The hypothesis being promulgated here is that one consequence of the dust trapped in the bulk sites of the fabric is the irreversible alteration of the performance parameters of the filter (with respect to the standard shake-cleaning). These changes need not be irreversible to all cleaning methods: witness the dramatic effect of the hand-washing with soap carried out on the bag tested under the normal cycle (Figures 5, 6). The hand-washing apparently succeeded in removing significant dust from the bulk sites of the bag, causing a dramatic drop in the drags. The fact that this washing step did not cause a corresponding decrease in the filter efficiency (or, similarly, an increase in the outlet concentration) allows the additional postulation that the bulk sites are subdivided into:

1) Sites which influence efficiency and which are sufficiently tightly bound to remain occupied throughout the wash cycle.
2) Sites which influence pressure drop and which are removed in the washing step.

Dust bridge orientation offers one possible explanation to make such a subdivision of bulk sites seem plausible. This model assumes that the trapped dust which offers the highest resistance to air flow is itself most susceptible to removal by even higher drag forces such as a water wash. The following paragraphs amplify this explanation.

From prior EPA work [Ref. 9] and elsewhere [Ref. 10] it is known that particle deposition on a fiber can occur in chains or filaments, rather than as a uniform coat--the first particle deposited on a clean

fiber adheres at a random site, but the second, third, and all subsequent particles tend to adhere to previously deposited particles rather than to another site on the clean fiber. Consequently the initial growth of dust cake is in the form of long thin chains or filaments of deposited particles. These growths extend outward from the surface of the initial deposition site into the gas flow until the aerodynamic forces break them apart or until they reach some adjacent point of support, such as another fiber or another growing particle chain. Once a particle chain establishes a stable anchor at its growing end, it has bridged a void and itself becomes a semipermanent surface capable of particle capture in directions normal to its axis of growth.

In the physical model suggested here, the orientation of these dust bridges with respect to the gas flow determines whether they will have a greater or lesser influence on pressure drop. If the dust bridges are regarded as primarily one-dimensional filaments, those that are aligned parallel to the gas flow have negligible influence on pressure drop (pressure drop is assumed to be proportional to surface area perpendicular to the gas flow across any plane of the filter); those aligned perpendicular to the gas flow present maximum impedance to gas flow. Most dust bridges will probably be oriented somewhere between these two extremes, having an orientation that is partly longitudinal and partly lateral with respect to the gas flow. The lateral component is that which both makes the largest contribution to pressure drop because of air drag, and is most vulnerable to removal by the even higher drag forces associated with a liquid flow; i.e., a wash. Thus, the effect of the wash cycle is to increase the ratio of longitudinally oriented dust filaments to those laterally oriented. Efficiency of dust removal depends on both orientations, although most likely the dependence varies with particle size. Capture by diffusion is favored by a longitudinal orientation; lateral orientation favors interception, inertial impaction, and sieving. Removal of lateral sites only would not necessarily reduce efficiency if most collection is due to diffusion.

The dust cake on the surface of the fabric favors the formation of lateral dust bridges because it lacks the depth of the fabric. The washing

action may just be a more effective removal of residual surface dust cake, characterized by a high ratio of lateral to longitudinal dust bridges,while the dust bridges formed within the three-dimensional fabric, being more longitudinally oriented, remain and preserve a high collection efficiency.

These thoughts are speculative; no further information clarifying the properties or location of these two types of bulk sites emerges from the data. Their existence is postulated to explain only one observation--the effect of washing. Additional experimental support for the concept seems warranted (or, alternatively, other explanations of the washing action) before accepting their existence.

A possible alternative explanation could be found by postulating a suitable electrostatic interaction attributable to the washing. Under the right conditions, electrostatic effects have been shown to reduce pressure drops while maintaining or improving filtration efficiency [Ref. 11]. This effect is exactly what the hand-washing of the bag brought about. The highly desirable consequences of the washing make further investigation and understanding of the interaction important follow-up work.

The final period of the life cycle of a fabric filter is the wear-out period. In this period the physical integrity of the bag is failing and enough leakage paths exist to permit significant dirty air flow through holes, voids, or non-homogeneous regions of the fabric filters with significantly different filtration properties. The drags decrease because of these "holes" and the outlet concentrations increase. The holes can be covered over by the dust cake, but the time required to do so becomes an increasingly large fraction of the total filtration period (Figure 4).

The wear-out is not necessarily abrupt and, if adequately monitored, provides ample warning of the coming deterioration. At the time the life cycle depicted in Figures 2 and 3 was declared complete and the bag classified as worn out, bag performance was still acceptable in an absolute sense. Even at the end of its life here, the bag's filtration efficiency was greater than 99 percent--testimony to the performance standards now routinely expected of fabric filters.

SECTION 6

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APPENDIX

CONVERSION FACTORS

To Convert From:	To	Multiply By:
$foot^2$	$meter^2$	9.29×10^{-2}
$inch^2$	$meter^2$	6.45×10^{-4}
$yard^2$	$meter^2$	8.36×10^{-1}
$grains/foot^3$	kg/m^3	2.29×10^{-3}
$grains/1000\ ft^3$	g/m^3	2.29×10^{-3}
lb (force)	newton	4.49
foot	meter	3.05×10^{-1}
inch	meter	2.54×10^{-2}
mil	meter	2.54×10^{-5}
yard	meter	9.14×10^{-1}
grain	kilogram	6.48×10^{-5}
lb (mass)	kilogram	4.54×10^{-1}
inch of water (60°F)	$newton/meter^2$	2.49×10^{2}
$lb/inch^2$ (psi)	$newton/meter^2$	6.89×10^{3}
$lb/foot^2$	$newton/meter^2$	4.79×10^{1}
foot/min (fpm)	meter/sec	5.08×10^{-3}
$foot^3$	$meter^3$	2.83×10^{-2}
$inch^3$	$meter^3$	1.64×10^{-5}
$yard^3$	$meter^3$	7.65×10^{-1}
oz/yd^2	kg/m^3	3.39×10^{-2}
°F	°K	$°K = \frac{5}{9}(°F + 459.67)$